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MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 294

MOTIVE POWER REQUIRED TO OPERATE A WIND TUNNEL.

By S. Ziembinski.

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TECHNICAL MEMORANDUM NO. 294.

MOTIVE POWER REQUIRED TO OPERATE A WIND TUNNEL.*

By S. Ziembinski.

The so-called "wind tunnel" type of aerodynamic laboratory is the most practical and the most generally employed at the present time. It consists essentially of a tunnel traversed by a wind of known velocity in which is suspended the object or model to be tested, the latter being connected with a dynamometric balance. The current of air is produced by a powerful fan.

The first wind tunnels were of small cross-section and the velocity of the wind was low, so that the fan absorbed but little power. The need of increasing both these factors soon became apparent. Very small models do not give sufficiently accurate results and the forces acting on the models are not always proportional to the square of the wind's velocity. It has therefore been necessary to try to produce wind velocities of the order of magnitude of those attained in aviation.

Since the power absorbed increases as the square of the diameter of the tunnel and as the cube of the wind's velocity, it soon becomes very large and necessitates a search for means to reduce the expenditure of motive power.

The Eiffel wind tunnel, designed for this purpose in 1911, at Auteuil, was provided with a convergent cone ab (Fig. 1) for the

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entrance of the air and with a divergent cone ce for its exit. The diameter of the tunnel bc, in which the experiments were performed, was 2 m (6.56 ft.) and the maximum velocity of the wind was 30 m (98.42 ft.) per second. The Eiffel tunnel was interrupted at the point where the experiments were performed and the whole was enclosed in a large air-tight room. When the fan was running, the air current produced in the room a negative pressure proportional to the square of the velocity.

The employment of the convergent and divergent cones thus saved half of the motive force theoretically necessary.

The eminent engineer Rith, to whom we owe the conception of these cones, reasoned as follows: The power required to produce a given air current is equal to the kinetic energy $\frac{mv^2}{2}$ of the air thrown off per unit of time into the surrounding air. It is therefore necessary to try to make the air leave the tunnel at as low a velocity as possible. In section c, immediately after the exit from the experiment chamber, the air has a high velocity V, while at the exit from section e, with a diameter D, the velocity v, is considerably smaller.

Since

$$\frac{V}{v} = \left(\frac{D}{d}\right)^2$$

we have

$$\frac{mv^2}{2} : \frac{mV^2}{2} = \left(\frac{d}{D}\right)^4$$

In the Eiffel laboratory $\left(\frac{d}{D}\right)^4 = \left(\frac{2}{3.8}\right)^4 = \frac{1}{13}$

The saving of power should therefore have been 12/13, but it was only 1/2, which shows that the principle applied is not exact.

When we had to design a still larger tunnel, we had to give more consideration to the expenditure of motive force by resorting to the theory of the exit cone and to the theory of the flow of a fluid through different orifices.

Ser's "Physique Industrielle," discusses the flow of a fluid through differently shaped orifices under the influence of a given motive pressure, teaches us that, if the flow takes place from a medium under higher pressure into another medium under lower pressure through an orifice in a thin wall, the fluid stream contracts greatly after passing through the orifice. If we place behind the orifice a cylindrical conduit of a certain length and of the same cross-section as the orifice, the stream still contracts, although in a less degree.

Consequently, outside air taken directly into a cylindrical tunnel, without any entrance cone, would separate from the walls, thus occasioning eddies and irregularities in velocity. Furthermore, the quantity of air passing through it would be smaller than if the contraction did not take place, while the power absorbed would remain equal to the power required in the case of a stream completely filling the tunnel. Consequently, there is a waste of power.

It is therefore important to avoid this contraction of the air stream. This is accomplished by placing at the entrance to the tun-

nel a convergent cone having an angle of about 30° at the small end. The air then fills the whole cylindrical tunnel uniformly, with the same velocity at the circumference as at the center and we may consider that this portion of the course does not present any loss of pressure.

Mr. Ser goes on to say that, if the exit of the cylindrical tunnel is provided with a slightly divergent cone, there is obtained, with the same motive pressure, an appreciable increase in the velocity of flow through the cylindrical portion of the tunnel. The same wind velocity can therefore be obtained with the expenditure of less energy. If the exit cone is well constructed, it can produce a very large negative pressure, considerably larger than the motive pressure necessary to produce the desired wind velocity.

On the basis of this information, we performed, in 1911-1912, a series of experiments for the purpose of determining the exact shape of the cones giving the maximum economy of power and, at the same time, the greatest uniformity of flow in the cylindrical portion of the tunnel

We began with an investigation of the physical phenomena of the air stream with the aid of the following apparatus. Our first need was a receptacle large enough to enable the air, forced into it by the fan, to lose all its velocity and its eddies before flowing through the orifice made in one of its walls for studying the air stream. This damping of the velocity at the entrance was transformed into pressure serving as the basis for the measurements in our experiments.

This receptacle or chamber A (Fig. 2) was constructed with both its lateral sides trapezoidal, for the purpose of converting the air stream into a flat form. The large end of chamber A was connected with the helicoidal fan by means of a divergent cone C prepared for subsequent experiments. M represents the electric motor. During the experiments it was found that, for an air stream attaining up to 40 m (131.2 ft.) per second in the section mm', the velocity of the air at the entrance to chamber A remained practically zero, the measurement being made with a particularly sensitive instrument.

The front end of chamber A is extended in the form of a parallelopiped a b c d a' b', in which we made an opening e f extending the whole height b b'. The top and bottom walls of the chamber were prolonged by two parallel glass plates g h i k represented by a k and a' k' in the elevation view. Between these glass plates we placed two flexible vertical walls l e m n and l' f m' n'. These walls consisted of hard smooth card-board reinforced by flexible strips of wood. These strips, attached to the outside of the card-board, served as points of attachment for the latter for off-setting the negative pressure in the moving air stream.

These card-board walls constituted the most important and useful part of our apparatus. Due to their independence of the rest of the apparatus, their mobility and flexibility, we were able to vary infinitely and gradually the shape of the cones and follow, as

it were, the air stream in its variations. In short, this very simple device saved us much time and expense, while allowing a very great latitude to our researches, a result we could not have attained by constructing a series of rigid cones. The use of glass for the other two walls enabled us to observe what took place inside the air stream.

The direction of flow at each point in the air stream was determined with the aid of a fine cotton thread attached to the tip of a streamlined rod. The wind velocity was measured with the aid of a double Pitot tube connected with a water manometer inclined 0.1.

At the beginning of the experiments, we removed the card-board walls, thus obtaining the flow through a thin wall a b (Fig. 3) with the characteristic contraction of the air stream at c d and the subsequent gradual divergence at an angle of about 7°.

We determined the direction of flow at each point and then measured the corresponding velocity. We found that the maximum velocity was in the contracted section c d and that it was appreciably greater than the velocity corresponding to the motive pressure according to the formula for the flow of air.*

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* On designating by
- m, the mass of the air;
- p, the weight;
- Q, the volume;
- v, the velocity;
- g, acceleration due to gravity;
- H, the height, in meters, of the column of air necessary to obtain the velocity v;
- h_m, the height of the same column expressed in meters of water;
- h, the height of the same column expressed in millimeters of water;

(Continued at bottom of p. 7.)

We were able to account for this apparent anomaly by the presence of the glass plates, the effect of which was to prevent the contraction of the air stream in the direction perpendicular to their planes. Mr. Ser states the fact, in the book referred to, that, whenever the contraction is prevented, the velocity of flow is increased. This fact was confirmed by our experiments.

Since we measured the static pressure in millimeters of water and the wind velocity according to the formula $v = 4\sqrt{h}$, i.e., also in millimeters of water, we should have obtained the same reading on both manometers. As the result, however, of the presence of

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(Continuation of footnote from p. 6.)

d, the weight of 1 m³ of water = 1000 kg (2204.6 lb.);
δ, the weight of a cubic meter of air,
We obtain:
the static energy of the air = p H;
the kinetic energy = $m\,v^2/2$

$$\frac{m\,v^2}{2} = p\,H$$

$$\text{but} \quad \frac{m\,v^2}{2} = \frac{p\,v^2}{2g} \qquad (1)$$

$$\text{and} \quad p\,H = \frac{p\,h_m\,d}{\delta} = \frac{p\,h_m\,1000}{\delta} = \frac{p\,h}{\delta} \qquad (2)$$

Formulas (1) and (2) then give us:

$$\frac{v^2}{2g} = \frac{h}{\delta}, \quad v^2 = \frac{2gh}{\delta}$$

We usually take $\frac{2g}{\delta} = 16$, thus obtaining:

$$v = 4\sqrt{h}$$

Formula (2) also gives us:

$$p\,H = \frac{ph}{\delta} = Q\,h$$

which is the expression for the static energy of the air under the pressure H or the kinetic energy of the air flowing with an output of Q m³ per second with a loss of pressure h.

the glass plates, when the static pressure was equal to h_s = 16.7 mm (.657 in.) of water, the velocity manometer gave h_d = 24.5 mm (.965 in.).

We could also easily account for the contraction of the air stream. The air flow began to be apparent a little before reaching the orifice. The directions of flow of the air filaments converged toward the orifice, the extreme filaments being parallel to the walls b e and d f of the compression chamber (Fig. 2), while the filaments situated nearer the axis were straighter. The resultant of all these filaments determined the general convergence of the air stream, which persisted for some time after passing through the orifice.

We also investigated the flow in the orifice itself. All the writers agree, in general, that the velocity of flow is smaller near the outside of the air stream and that it increases toward the center. We found that this was not really so. The variation was only apparent and was obtained by taking the measurements parallel to the axis of the air stream. When, however, the actual direction of flow at each point was first determined (Fig. 3) and the velocity measurements were taken in the directions found, we were able to demonstrate that the true velocity of flow was constant everywhere from the axis of the stream to the immediate vicinity of the wall. This velocity and the velocity in the most contracted region were inversely proportional to the diameters ab and cd (Fig. 3) of the air stream. This proportionality proved the accu-

racy of our measurements, since the output of air was naturally the same in both sections.

The boundary region between the air stream and the surrounding air was filled with eddies or vortices produced by the striking of the moving against the motionless particles and the dragging of the latter into the motion. On the outer margin of this region we noted a motion of the air toward the air stream. Close to the exit side of the orifice there were hardly any vortices because too small a period of time had elapsed for the exterior air to produce them. The exterior currents were strictly perpendicular to the contour of the stream and their intensity was very great. Farther away from the orifice these currents became weaker and deviated in the direction of the stream and the vortices became more numerous. If our apparatus had been long enough, the whole air stream would certainly have been dispersed in vortices.

In spite of the fact that these vortices appreciably disguised the real shape of the stream, we were able to show that the latter, after the convergent portion and after the smallest cross-section, became appreciably divergent, closely following the angle 7°, which is generally mentioned as the natural angle of a free air stream and, at the same time, as the best angle for divergent tunnels.

The phenomenon of the exterior currents is very interesting because it demonstrates the negative pressure which reigns within the moving stream. When air flows freely, this negative pressure remains unused, but, if it could be utilized, it would increase the

velocity of flow by adding to the motive pressure and this was the object of our researches.

In fact, on installing the previously described card-board walls and placing them on the boundaries of the freely flowing air stream, we found such a difference of pressure between the outside and inside, that a very strong pressure on the glass plates failed to offset it, so that we were compelled to attach the card-boards firmly to exterior uprights.

After these precautions had been taken, our predictions were fully justified by the experimental results. With the same motive pressure h_s = 16.7 mm (.657 in.), we had in the free current h_d = 24.5 mm (.965 in.). In a perfectly similar air stream, but bounded by card-boards, we found h_d = 44 mm (1.73 in.), i.e., an almost double negative pressure corresponding to an increased velocity in the proportion

$$\frac{V}{v} = \sqrt{\frac{44}{24.5}} = 1.35$$

In this experiment, the convergent angle was 30° and the divergent angle 7° (Fig. 4), according to the observation of the free current and the recommendations of Mr. Ser. The passage from one part to the other was made very gradually. In the free air stream this gradual passage was a necessity, but, in the confined stream, our subsequent experiments demonstrated the advantage of deviating from this method.

We then tried to discover the shape required by the walls of

the convergent and divergent portions and especially whether it was better to concave them, as Eiffel did, or to make them rectilinear. The experiments demonstrated the incontestable advantage of rectilinear walls, especially for the exit cone, because such walls give a more uniform current and allow the air stream to fill the exit cone.

With concave walls, the air stream fills only the beginning of the exit cone and then separates from the walls, the space between the air stream and the walls being filled with vortices, which cause a loss of energy. In fact, from the instant the separation took place the velocity of flow diminished.

As regards the angle of the exit cone, all the writers recommend 7° as giving the best results, but our experiments have clearly demonstrated the superiority of 15°. For $\alpha_2 = 7^\circ$ we obtained 44 mm (1.73 in.) and for $\alpha_2 = 15^\circ$ we obtained 58.5 mm (2.30 in.), with a perfect filling of the exit cone.

This result is of prime importance in designing a wind tunnel for which the diameters of entrance and exit are given. The angle of 7° requires an excessively long exit cone, while 15° reduces this length by more than one-half, thus effecting a great saving in the construction of the tunnel.

We obtained still better results by clearly separating the convergent and divergent portions and finally, when we had arrived at three parts with rectilinear generatrices and sharp angles of union, we obtained h_d = 66 mm (2.6 in.)

For the sake of completeness, it should be further noted that

we obtained $h_d \doteq 73$ mm (2.87 in.) by making the convergent angle 45 and 60°. In these cases, however, the velocity in the cylindrical part (i.e., in the useful part) of the tunnel became irregular and much stronger at the margin than at the middle of the air stream, because the very open entrance angle collected too much air, which remained near the walls and increased the velocity in their vicinity.

The latter device is not applicable, therefore, to the wind tunnel, though it indicates the possibility of finding an angle between 30 and 45° which would give a slightly greater velocity at the periphery of the tunnel. In some cases this velocity excess of the marginal layer might offset the considerable friction of the air stream against the stagnant air in an open tunnel of the Eiffel type or against the walls of the tunnel.

Returning to our discussion, we wish to emphasize the very evident advantage of sharp angles of union of the cylindrical portion with the conical portions of the tunnel.

In fact, no application has yet been made of this result, although our experiments were performed twelve years ago. In any event, one would hesitate to adopt it, for the lack of a suitable experiment enabling an immediate comparison. Our apparatus with adjustable card-boards is well adapted to this determination.

In fact, after having begun with apparatus having very gradual transitions between the three portions (Fig. 4), we then marked the limits of a cylindrical portion and gradually reduced the angles of

union at the entrance and exit.

In keeping with these changes, we noted in the manometer column a parallel increase of the velocities h_d. After confirming this improvement, we made incisions in the slats reinforcing the card-boards and even broke the card-boards at the ends of the cylindrical portion, in order to give them sharp angles, and then put them back in the apparatus.

At the convergent end, we found an absolutely regular entrance of air. The velocity of the air was the same from the center to the margin and the air filaments were strictly parallel. This arrangement rendered it possible to dispense with all devices for straightening the air filaments, which was a decided advantage.

In the divergent portion we first allowed the card-board to assume a rounded shape under the influence of the interior negative pressure. We then pulled on the exterior cords at the origin of the divergent portion, so as to change it gradually to a sharp angle. The level of the velocity manometer (connected with a Pitot tube placed in the cylindrical portion) then rose as though there were some mechanical connection between the cord and the level of the water. The experiment was very expressive in this sense. The more the card-boards were separated, the more the pull on the cords increased, i.e., the more the negative pressure increased at the origin of the exit cone and the more the velocity manometer (in the cylindrical portion) rose. All this took place, however, only up to a certain critical point. When this point was passed, the pull

on the cords decreased suddenly accompanied by a corresponding drop in the velocity manometer, showing that our invisible mechanical connection had been broken. On considering what had taken place in the air stream, we found that it had separated from the walls and that vortices had formed between the stream and the walls.

We repeated the same experiment several times and every time confirmed the parallel increase of the angle of divergence and of the velocity in the cylindrical portion up to the critical angle, which was a little above 15°. The velocity was the greatest when the exit cone began with a sharp angle without any rounding off. The experiments showed clearly that rounding the angle at the junction point reduced the velocity in the cylindrical part.

With a convergent angle of 30°, a cylindrical part definitely limited by sharp angles and a divergent angle of 15°, we obtained h_d = 66 mm (2.6 in.) for h_s = 16.7 mm (0.657 in.), as already mentioned.

It is well to remark here that the presence of the parallel glass plates increased the velocity of the air, when the card-boards were absent and when the flow took place through a thin wall. When, however, the card-boards were introduced in suitable shapes, the plates played, on the contrary, a negative role. In fact, after its passage through the orifice of the box, the air stream had to spread only in one dimension, parallel to the glass plates, while keeping a constant thickness vertically. It is logical to assume that the forcing of the air stream to expand in only one of

its two dimensions would increase its negative motive pressure (depression motrice) somewhat.

Consequently, the above experiments should be considered only as a purely physical investigation of the phenomena of an airstream.

In order to obtain definite data, directly applicable to the designing of a wind tunnel, there yet remained to be made a series of experiments with actual cones, first to verify the phenomena observed, next to determine the new factors and lastly, to obtain definite numerical values with the aid of an accurate model of the tunnel.

There remained, for example, to determine which of the two above-enunciated theories was true and especially whether economy in motive force is a function of the ratio of the diameters of entrance and exit of the exit cone, as Mr. Rith supposed, or whether the predominant role is played by the negative pressure created at the origin of the exit cone.

In order to solve this problem, we used the conical tube C (Fig. 2) employed in previous experiments. We eliminated chamber A with its glass plates and allowed the air to pass directly from the conical tube into the surrounding atmosphere. For driving the electric motor, we had a set of storage batteries giving a constant current measured with the aid of instruments of high precision. Furthermore, as the result of a preliminary calibration, we knew the output of the motor for every load and speed.

The length of the exit cone was eight times its small diameter.

After each experiment we shortened the exit cone, at its larger end, by an amount equal to its small diameter and measured the power required to obtain the same air velocity through the propeller.

Since it was impossible for us to obtain exactly the same air velocity in every experiment, we had to reduce all the powers to the same velocity of 15.5 m (50.85 ft.) per second, corresponding to a pressure of 15 mm (.591 in.) of water. Remembering that the power absorbed is measured by Qh (product of the output of air per second times the corresponding pressure read in mm of water) and that Q is proportional to v (i.e., to $\sqrt{h}$), we see that the power absorbed is really proportional to $h^{3/2}$. Consequently, if, with a pressure h, the power absorbed by the propeller shaft were W, it would be $W' = W\left(\frac{15}{h}\right)^{3/2}$ for a pressure of 15 mm (.591 in.). This is the formula we adopted for the correction.

Under these conditions, we performed a series of experiments with lengths of the exit cone equal to 8, 7, 6, 5, 4, 3, 2, 1 times the small diameter and finally without any exit cone at all. The results are shown in Fig. 5, in which the abscissas represent the ratios of the length of the exit cone to its small diameter and the ordinates represent the powers absorbed, in watts, reduced to the pressure of 15 mm (.591 in.) of water. The diagram demonstrates that the presence of the exit cone affords a real saving of power. The power absorbed diminishes rapidly with the first lengths, then remains stationary and even increases in passing from 4 to 5 diameters and then diminishes again, although much slower

than at first. There is produced, therefore, at a given point, a phenomenon resembling the crest of a wave.

This experiment justifies the theory that only the first portion of the exit cone produces the desired negative motive pressure. The length of the exit cone should be limited to that required to make the air take the exact shape of a divergent cone with a given angle.

According to our experiments, the best length would be three times its small diameter for an exit cone with an angle of 7° at its small end. In fact, such an exit cone had been made before our experiments demonstrated the superiority of the 15° angle.

We then performed a series of experiments with different conical tubes joined together so as to constitute a small wind tunnel (Fig. 6). In this system the air first entered a convergent cone A (entrance cone) from which it passed into the divergent cone C (exit cone). Between these cones the airstream was expected to retain for some distance a constant cross-section and consequently a a uniform velocity, this space constituting the useful portion (experiment chamber) of the tunnel. In many laboratories, this portion is surrounded by a cylindrical tube thus giving rise to the term "tunnel." Mr. Rith, the designer of both the Eiffel laboratories, modified this portion, however, in an extremely ingenious manner, for the purpose of facilitating the experiments. He demonstrated that, if the experiment chamber traversed by the tunnel is made air-tight, the walls of the tunnel may be removed and the air will

traverse the chamber in a homogeneous stream, from the entrance cone to the exit cone, without mingling with the still air in the chamber. This device enables a much better observation of the course of an experiment and a much greater accessibility to the model being tested. We therefore endeavored to apply this principle by simply joining the cones A and C with the aid of an air-tight chamber B. On leaving this chamber, the air passed into the exit cone C, which was the principal object of our investigation. At the end of the exit cone we placed the fan D, which we chose of the helicoidal type, rather than of the centrifugal type, for several reasons. First because the maximum efficiency of the helicoidal fan corresponded precisely to the small motive pressures we desired to obtain, while the good efficiency of the centrifugal fan corresponded to considerably higher pressures. Secondly, because the helicoidal fan better conserved the general shape of the airstream, a matter of great importance to us. Lastly, a helicoidal fan cost considerably less than a centrifugal fan for the same diameter of intake.

The small fan used in these experiments was purchased of the constructor who was to furnish the large fan. We were therefore sure of having the same efficiency for the same negative motive pressure and the same wind velocity, which was of great advantage for the computations.

The fan was placed after the experiment chamber, rather than before it, because we thus obtained a more homogeneous airstream in the experiment chamber, since the air was full of eddies after

leaving the fan. The fan was placed at the farther end of the exit cone, first, to remove it as far as possible from the experiment chamber and protect the latter from every possible perturbation; secondly, because large quantities of air, with such small negative motive forces, required very large diameters; lastly, because, as will be subsequently shown, it was easy to produce a second negative pressure, and therefore another saving of motive power, by placing another exit cone after the fan.

We first verified the advantage of the angle of 15° over that of 7° for the exit cone by making two cones having the same diameters of entrance and exit and differing only in the angle at the apex. In order to obtain the same wind velocity of 40 m (131.2 ft.) per second, the 7° angle required 2400 watts, while the 15° angle required only 2070 watts, or a saving of 14%. The adoption of 15° therefore effected a saving in power, in addition to the saving in the cost of construction, resulting from the reduction in the length of the tunnel.

We have already mentioned that the wind velocity produces, at the beginning of the exit cone, a negative pressure, which, added to the negative motive pressure, becomes another source of economy. In order to derive the full benefit from this negative pressure phenomenon, the exit cone must have a certain minimum length with respect to its small diameter. If, however, the exit cone is prolonged beyond this useful length, no additional benefit is obtained.

If, however, the fan is placed after the exit cone and if a

second exit cone is placed after the fan, the second cone will act as an independent device in producing additional negative pressure and additional economy of motive force. We verified this with our last tunnel which showed an absorption of 2070 watts when provided with the second cone. On removing the latter, the required power increased to 2390 watts, i.e., almost to the power required for the 7° cone.

The length of the second cone was equal to only one small diameter. It did not appreciably diminish the power absorbed, but the flow of the air became much more uniform, which is of prime importance in a wind tunnel.

It was also noted that, in the entrance plane of the fan, the wind velocity at the periphery fell almost to zero, so that the failure of the 15° angle might be inferred, on supposing the air incapable of such sudden expansion. On a closer investigation of the phenomenon, however, it was found that the air current filled the cone from its beginning to within a short distance of the fan and that the airstream became convergent from this point because of the sudden acceleration produced by the fan (Fig. 7), so that the tips of the blades revolved in still air without doing any work. In order to remedy this defect, we placed between the exit cone and the fan a short cylindrical portion, which greatly reduced the peripheral zone of inaction. The result confirmed our expectations. Instead of the preceding 2070 watts, we now expended only 1710 watts, thus saving 17.5%.

It is undoubtedly true that a still greater saving could be obtained by providing the extremity of the cone with a swelling of greater diameter than the diameter of the fan (Fig. 8), so that the airstream would have time to pass gradually from the divergent to the convergent form, in order to enter the fan correctly without separating from the walls of the cone. We were unable, however, for lack of time, to experiment with such a device.

In all the experiments thus far tried, the experiment chamber was arranged as shown in Fig. 6, i.e., according to the Eiffel system, in which the air traverses the chamber as a free stream. At high velocities, this stream became very irregular, because the friction and the shocks caused it to mingle with the still air, so that the whole experiment chamber was full of eddies. We were able to observe this disadvantage in several wind tunnels constructed on the Eiffel plan, when the air attained rather high velocities.

This dispersion of the airstream has the double disadvantage of impairing the accuracy of the experiments and of increasing the motive power, a portion of which is absorbed by the eddies.

In order to remedy this disadvantage, we endeavored to separate the still air from the airstream by placing in the experiment chamber an actual tunnel joining the entrance cone to the exit cone. Since we expected a saving of power from this device, we decided to increase the diameter of the airstream in chamber B, in order to keep within reasonable limits for reading the power absorbed. We effected this increase in diameter by shortening the entrance and

exit cones at their small ends. Notwithstanding these shortenings, the length of the exit cone was still more than thrice its small diameter, so that we could consider the efficiency of the system unimpaired and so that, for the same velocity, the required power would increase in proportion to the area of cross-section or the square of the diameter.

In fact, after we had increased the diameter from 218 mm (8.58 in.) to 284 mm (11.18 in.), without introducing the tube for enveloping the airstream, the power absorption was increased so much that it was impossible, with our engine, to attain the same velocity as before, namely 40 m (131.2 ft.) per second. But, after we had further increased the diameter to 305 mm (12.01 in.) and had introduced the enveloping tube, the power-absorption dropped to 2000 watts.

Since this experiment was performed without the cylindrical portion before the fan, it was comparable with the one in which the absorbed power was 2070 watts. In the new tunnel the volume of air delivered per unit of time was almost double what it was before, since

$$\left(\frac{305}{218}\right)^2 = 1.95.$$

Lastly, since the required power dropped at the same time from 2070 to 2000 watts, the new tunnel was fully twice as economical as the previous one, since

$$\left(\frac{305}{218}\right)^2 \times \frac{2070}{2000} = 2$$

It may therefore be claimed that, in a wind tunnel of the Eiffel

type; for a velocity of 40 m (131.2 ft.)/sec. and a sufficiently long free space, half the motive power is absorbed by the eddies in the experiment chamber.

We therefore resolved to adopt a mixed system. We constructed an air-tight experiment chamber (Fig. 8) with an actual tunnel in this chamber separating the still from the moving air throughout its entire length and with a 75 cm (29.53 in.) slot (in the full-sized tunnel), sufficient to introduce and to observe the models. The edges of this slot were provided with flanges designed to prevent the propagation of eddies through the chamber. These experiments having been reported to the Eiffel laboratory, the device has been partially applied with a saving in motive power and the elimination of eddies in the experiment chamber.

Our time being limited, we were unable to construct a tunnel corresponding exactly to Fig. 8. Such a tunnel, provided with an enlargement of the exit cone just before the fan, would certainly have proved more efficient than the last tunnel experimented with. Since we were unable to try the corresponding experiment, we decided, in order to allow a sufficient margin of security, to calculate the power necessary for a large tunnel on the basis of the results of the last experiment made, or 2000 watts for a wind velocity of 40 m (131.2 ft.) per second in an airstream of 305 mm (12.01 in.) diameter.

We first calculated the efficiency of our small tunnel. According to the calibration abaci, the efficiency of our motor, for the given velocity and load, was 0.52. Consequently, on disregarding,

for the sake of greater security, the loss due to the belt, we had on the fan shaft

$$2000 \times 0.52 = 1040 \text{ watts} = 1.4 \text{ C.V.} = 105 \text{ kgm } (759.5 \text{ ft.-lb./sec.}$$

and the output of air was

$$Q = Sv = \frac{\pi d^2}{4} v = \frac{\pi\, 0.305^2}{4} 40 = 2.92 \text{ m}^3 (103 \text{ cu.ft.})/\text{sec.}$$

Since the efficiency of the fan, according to the diagram furnished by the maker, was 0.50, the power absorbed by the fan was

$$P = 105 \times 0.50 = 52.5 \text{ kgm } (379.7 \text{ ft.-lb.})/\text{sec.}$$

but, since we also have

$$P = Qh = 2.92\ h$$

we find, on making the two quantities equal,

$$h = \frac{52.5}{2.92} = 18 \text{ mm } (.71 \text{ in.}) \text{ of water},$$

this being the negative pressure produced by the fan in giving a wind velocity of 40 m (131.2 ft.) per second.

The exit cones selected enabled us, therefore, to save 82% of the required power or, in other words, to reduce it in the ratio of 6 to 1, without allowing for the saving due to the enlargement of the exit cone just before the fan, the loss due to the belt (neglected in the efficiency calculation) and the improved efficiency of the fan in passing from the small to the large tunnel. It is therefore reasonable to assume that the large tunnel would give a power reduction in the ratio of at least 7 to 1.

It only remained for us to determine the characteristics of the

wind tunnel to be built on the basis of the results obtained with the last tunnel tested. In order to do this, we could have calculated the required power, according to scale. On the contrary, however, we computed the dimensions required for the given motive power, since 175 HP at the fan shaft was available for our tunnel. The scale could be determined by means of the power formula already referred to:

$$P = Qh = \frac{\pi d^2}{4} vh$$

Since h and v remain the same in both cases, it is obvious that P varies as the square of the linear dimension or as the square of the scale. The latter is therefore the square root of the ratio of the powers. Since the model experimented with absorbed 1.4 HP, our scale is

$$E = \sqrt{\frac{175}{1.4}} = 11.2$$

We can therefore take for the useful diameter of the tunnel

$$D = 0.305 \times 11.2 = 3.4 \text{ m } (11.15 \text{ ft.})$$

and for the diameter of the fan

$$D_1 = 0.550 \times 11.2 = 6.13 \text{ m } (20.11 \text{ ft.}).$$

According to the data furnished by the constructor, the best fan for the required output and negative pressure of 18 mm (0.71 in.) of water should have a diameter of 8 m (26.2 ft.) to give an efficiency of 60% in this case. To avoid making the tunnel too large and too expensive, we decided, however, to limit the diameter of the fan to 6 m (19.7 ft.).

This tunnel, with a wind velocity of 40 m (131.2 ft.) per second and a diameter of 3.4 m (11.15 ft.), required only 175 HP, instead of the 1000 HP it would have required without the exit cones. These figures are sufficiently eloquent in themselves.

Various circumstances have prevented the execution of this project. If, however, it should now be resumed, it would be better to employ a propeller with several blades instead of a helicoidal fan.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

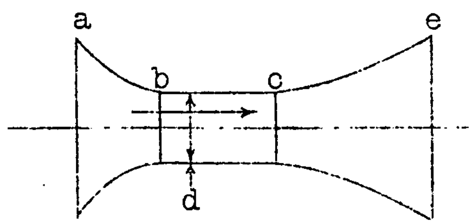

Fig.1.

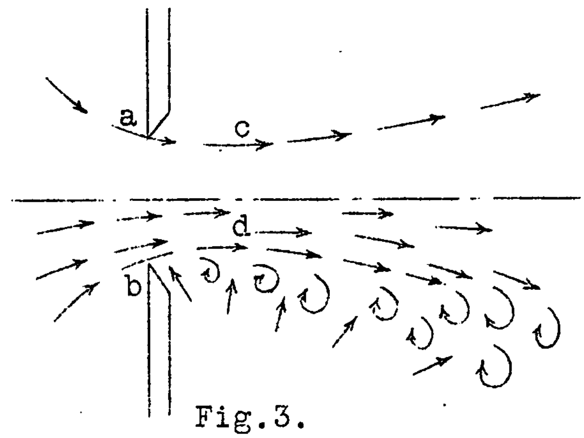

Fig.3.

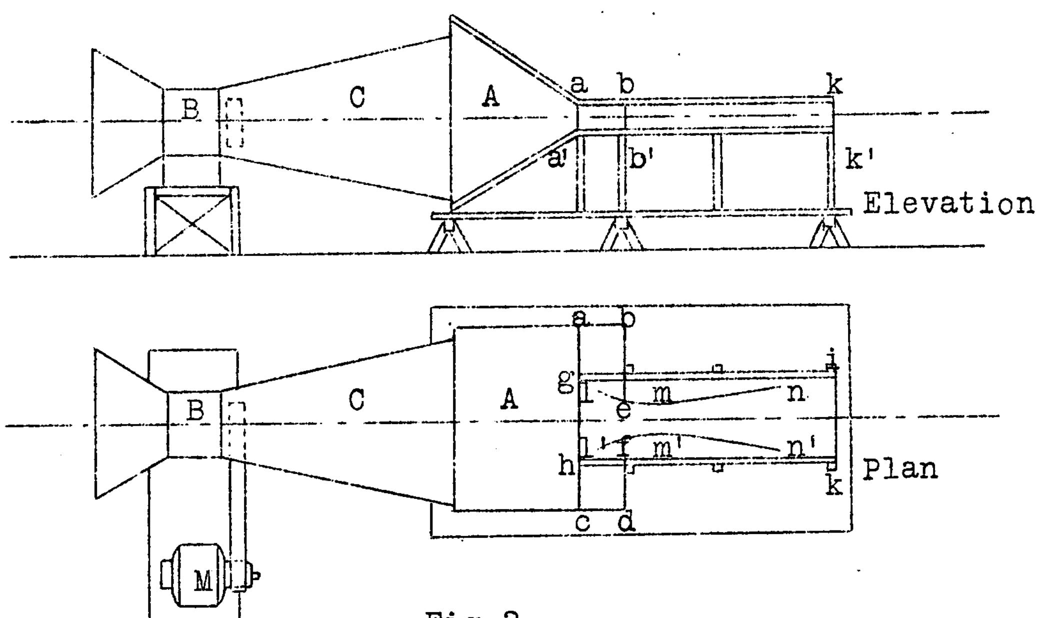

Fig.2.

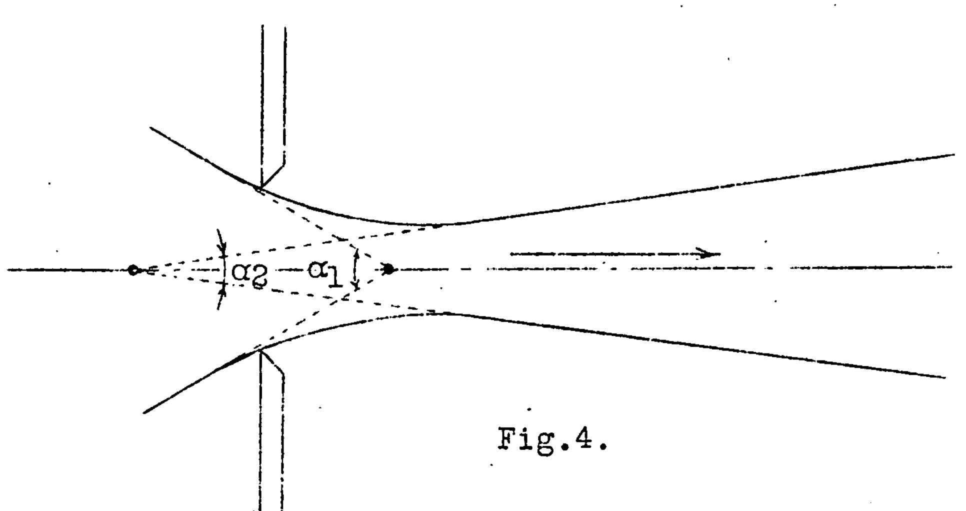

Fig.4.

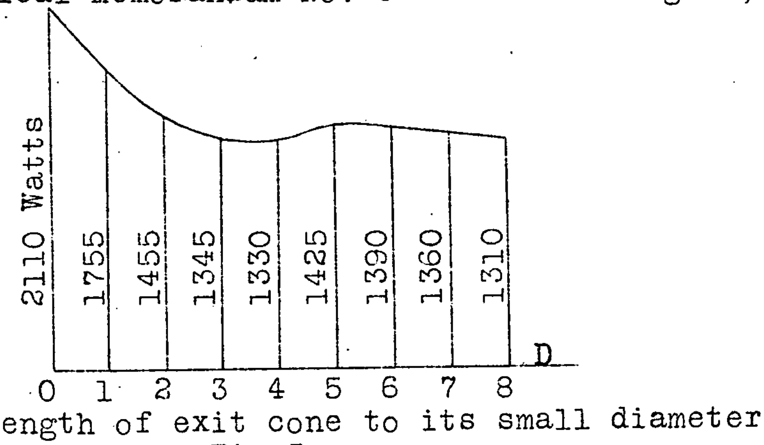

Fig.5

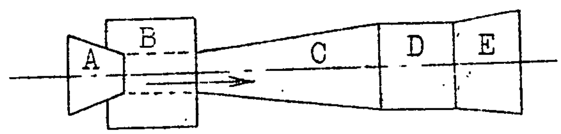

Fig.6

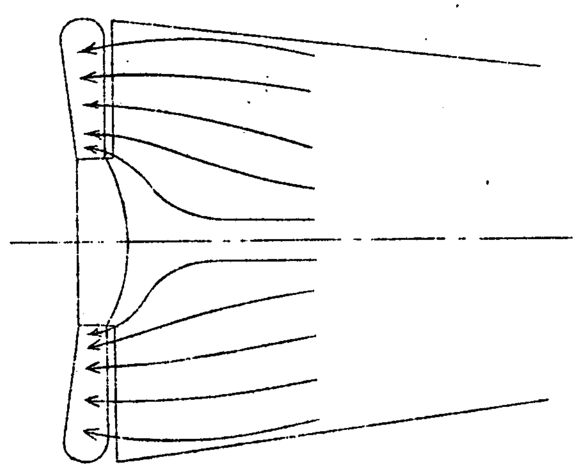

Fig.7

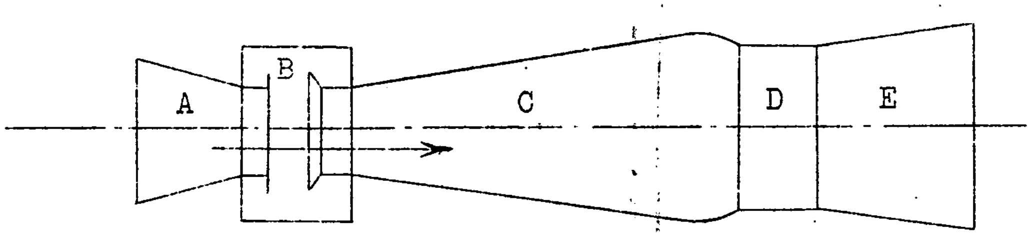

Fig.8